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RESEARCH ARTICLE

Applying large electric double layer capacitor systems

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Abstract This paper provides an insight into the specifications for electric double layer capacitor systems (EDLCs), design issues and production technology. It focuses on systems with power ratings far in excess of 100 kW and with short cycle times. As a result, a major topic of interest is EDLC cooling. Several cooling concepts are compared with each other based on experimental data. This is done for four EDLC configuration types. Mechanical aspects and diagnostics of the electric and thermal system are also covered.

Keywords EDLC · Electrochemical double layer capacitor · System integration · Automotive

Abbreviations

EDLC	Electric double layer capacitor
RPM	Rotations per minute, the rotation rate
C-box	Compact box design

1 Introduction

This paper provides an insight into the specifications for electric double layer capacitor (EDLC) systems, design issues and production technology. It shows some of the steps that were taken to simplify the EDLC system and to ensure its reliability. The mechanical, thermal and electric design is also analysed. After summarising the possible applications of EDLCs, the paper focuses on the hybrid bus application. In Sect. 3, the system specification is investigated. In Sect. 4 the mechanical, thermal and electric concepts are evaluated, while in the subsequent section there is a discussion on mainly diagnostic possibilities.

VITO, the Flemish research organisation, has been working with large EDLC systems since 2005, mainly integrating them into high power, high voltage (up to 900 V) systems. This activity was transferred to a spin-off company, Bluways, in 2009 for commercialisation. This company took over the ISE corp. (USA) in 2011. This article is based on the experiences with the various systems that were developed in these three entities.

2 Systems with EDLCs

The behaviour of EDLCs has widely been described since 2000 [1–6]. EDLCs are used for power electronics to stabilise the DC bus voltage between the energy source and the output in new designs [7–9]. They can be used for photovoltaic and wind energy generation [10–12]. Larger groups of EDLCs are used as hybrid drivelines for cars [13–19], for busses [20] and for railway applications such as trams and underground rail systems [21–24]. The EDLCs can be stationary, installed in railway systems [25, 26] to recuperate the braking energy that is fed back to the electricity system. Heavy duty applications and forklift trucks with EDLCs [27–31] have also been described in the literature. Many articles relate to drive lines with fuel cells [32–34].

One of the most notable applications of large EDLCs is without doubt the hybrid bus. For this application, bus

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Fig. 1 A hybrid waste collection truck with 0.5 kWh EDLC storage on the roof

Fig. 2 A hybrid floating harbour crane. The EDLCs are mounted below deck

manufacturers defined requirements that resulted in an EDLC system that could be used for other applications: waste collection trucks (Fig. 1) and harbour cranes (Fig. 2). Up to now, the only goal of using EDLCs in these applications has been to reduce energy consumption. This is done primarily by relying on brake energy recovery. Operation of the combustion engine at its sweet spot contributes only marginally to energy savings. Modern diesel engines have a very wide operating window in which specific fuel consumption is close to the best value: the sweet spot is large and “flat”. Furthermore, engine RPM changes contribute to fuel consumption increase when increasing RPM but to fuel consumption decrease when lowering RPM, so the power surges themselves contribute only marginally to fuel consumption. A common misunderstanding is that engines can be sized smaller due to the EDLCs. Smaller ICEs tend to have lower efficiency than larger engines. In addition, the energy stored in a capacitor is too limited to guarantee full performance of the vehicle, e.g. when driving uphill. For this reason, manufacturers are reluctant to install considerably smaller ICEs when capacitors are the only storage device on the vehicle. So, in practice, fuel consumption is reduced mainly by brake energy recovery (that is reused during acceleration). The reduction of fast engine transients and, where applicable, downsizing the engine contribute less to total fuel savings. For this reason, waste collection trucks and harbour cranes offer a higher potential gain from EDLCs as these machines have shorter work cycles than a city bus. A city bus will stop every 800 m, or with an average speed well under 10 m/s, every one and a half to two minutes. A waste collection truck will start/stop every several tens of metres, while a harbour crane will grab a load every minute. The harbour crane recovers both kinetic and potential energy. The kinetic energy is recovered when swinging the load at a peripheral speed of well over 5 m/s. Typically, the crane transfers bulk (e.g. coal) from a ship to a truck or a heap. In the ship, the bulk is near the waterline level so the crane has to deliver unrecoverable potential energy to the load. Potential energy can only be recovered when the load is lowered, e.g. after clearing an obstacle and only until the load itself is dropped (which may be a few metres over the heap). This results in potential energy recovery over no more than a few metres.

Several companies have developed EDLCs for bus applications, the most well-known being ISE corp. (USA). The workhorse of ISE was the Thunderpack, an open module with internal air cooling. Bluways builds systems that are sealed to be water-tight with external cooling.

The EDLC systems in this article are manufactured for busses, harbour cranes and waste collection trucks.

3 Requirements and system specification

This paper focuses on EDLC systems that are capable of delivering up to 180 kW with hybrid busses as application. The basic EDLC system used in most of these applications enables storage of 500 Wh between 400 and 700 V. An amount of 0.5 kWh of energy is sufficient to accelerate an articulated bus on a flat road to a speed compatible with inner city operation. For any other circumstances, an energy storage system considerably larger than 0.5 kWh would be required. For the given voltage window, 0.5 kWh can be stored in 280 EDLCs of 3,000 F, which is a common size on the market.

Bus manufacturers supply a reference cycle (Fig. 3) that has been used to design the basic EDLC system. This cycle reveals an energy recovery potential of 0.35 kWh if no current limitations are taken into account. This is also the kinetic energy in a bus weighing 13 metric tons moving at 50 km/h. The cycle represents a start/stop sequence of a

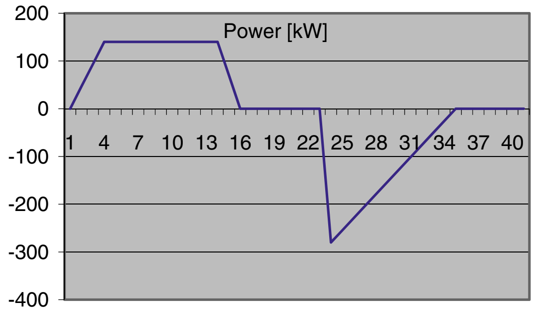


Fig. 3 Capacitor storage power requirement specification for hybrid busses. The time axis is expressed in minutes

bus and results in currents up to 340 A for short times and an RMS value for the current of 187 A. However, as this cycle does not include the time the bus is stopped at the bus stop, the EDLC system was designed for 150 A RMS. This is a conservative assumption: data from bus operation in two Flemish cities, Ghent and Leuven, show that the ½ hour RMS value of the current usually is under 100 A and rarely exceeds 120 A.

A second aspect of the system design is the interfacing to the electric system to which it is connected. The energy stored in an EDLC being proportional to the difference of the square of upper and lower operating voltage, a DC/DC converter is usually required to connect the EDLC string to the DC bus of the application. Different methods for this are available [35, 36]. In many cases of hybrid busses, the EDLC systems are used in combination with the Siemens Elfa driveline system [37] consisting of automotive grade inverters and electric machines. In these cases, the DC/DC driveline is implemented using one or two spare IGBT bridges of the motor inverters. The addition of a DC converter also enables precise control of energy to and from the storage device.

As the EDLC systems contain many cells in series, balancing plays an important role. Some methods have been described by other authors [38, 39].

In regions where rain and humid conditions occur, the EDLCs have to be well protected against humidity. This quickly translates into the specification of water-proof against splashing of water and dust-proof, being designated as IP54 protection [40]. This in turn leads to thermal issues, which have to be studied in detail. Three strategies are examined in this article: forced air cooling, natural convection cooling and liquid cooling. Although these are normal engineering options, they involve specific possibilities and constraints due to the cylindrical EDLC shape and also due to the influence of the ambient temperature. This will be substantiated in the next section.

The engineers applying large EDLCs are confronted with the following issues:

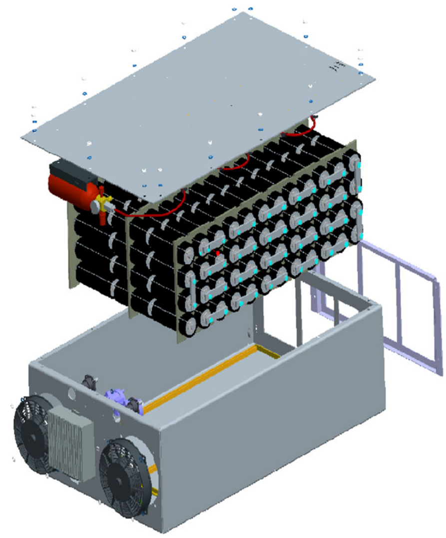


Fig. 4 The open EDLC system, known as ISE's Thunderpack

1. Mechanical integrity, cell interconnections, isolation, electrical protection
2. Thermal management, cooling
3. Interfacing to the rest of the drive system
4. Individual cell balancing
5. Diagnostics

Cell balancing is an important topic that can be described in a separate article and is partly covered in [38, 39]; it therefore lies beyond the scope of this paper.

Four EDLC system lay-outs are studied here:

An open system (the Thunderpack configuration in Fig. 4).

– Large boxes with 56 EDLCs of 3000 F inside in combination with a balancing and monitoring system. The capacitors are stacked in the most compact way in order to limit the system size. The box is rated IP54.
– A medium box with 20 capacitors in a box and IP54 grade, called the 'standard' configuration in this paper, see Fig. 5. The capacitors are stacked with more interspace: the EDLCs are installed 3 cm apart (Fig. 5).
– 18 cells in a compact box with IP54 grade, see the same figure, are mounted comparable to the large module.

4 Concepts

4.1 Mechanical

In the design of the EDLC system for hybrid busses, the size limitations on the roof of the bus and the specific climate conditions must be taken into account. A modular approach

is recommended for reasons of installation, cooling and in-the-field replacement. A system based on EDLC modules also contains a module that is filled with control electronics. The body of each module also acts as a fast slide system for easy connection with the whole system. Interconnection of the modules can be performed by means of a central interconnection box. The electronics box contains the system controller, fan controller, contactors and extra safety equipment such as a metal-oxide varistor (MOV) for transient voltages. Electric insulation is also an important factor. Every EDLC module is designed to withstand 20 kV of voltage peaks. For the purpose of monitoring the entire system, an insulation detection system must be incorporated.

In the case of the open system, all capacitors are in two units. For the system based on the large modules, 5 EDLC modules are needed. In case of the 'standard' modules, 14 are required as is the case for the compact configuration. Although a system based on the compact modules has fewer capacitors than a system based on the standard modules, the energy content is the same due to a more powerful balancing system that enables energy content to be optimised in every single capacitor.

The described EDLC large modules are constructed in such a way as to guide the internal heat to external cooling fins. This is performed by applying the heat points of the capacitors onto the cooling fins, separated only by electrical insulation. These heat points form the connection of the EDLCs with the bus bars. To minimise the heat production and to guarantee a lasting connection even when subjected to vibrations, shrink fitting this bus bar is insufficient, so laser welding of the bus bars is performed. An air flow over the fins provides control over the heat dissipation. Thermal control is realised with PWM-steerable fans and a duct for guiding the air flow in combination with a thermal monitoring system.

Regarding the 'standard' boxes, the system is a redesign of the large boxes that offers a significantly larger cooling surface for the modules. The capacitors are mounted in specially shaped bus bars that provide a heat conduction path through the electric insulator, which is three times larger than in the first design. An added advantage of the 'standard' EDLC modules is that they are lighter and therefore easier to exchange.

The whole system is covered by a hood to protect it against direct impact of weather conditions such as sunlight and rain (Figs. 6, 7). The IP54 rating of the modules is ensured by the necessary sealing and IP54-compliant connections. The majority of the vibrations of the bus are

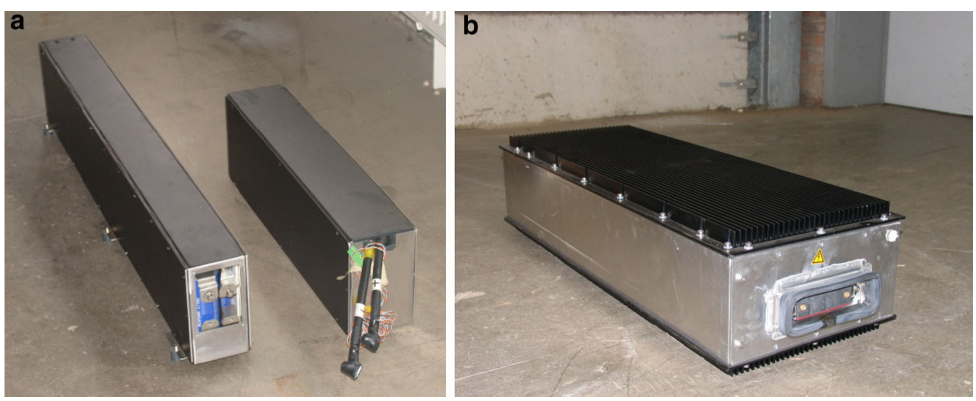


Fig. 5 **a**, **b** (from *left* to *right*): *Closed boxes* with IP54 grade: the 'standard' one with 20 capacitors, the compact box with 18 capacitors and the 56 cell module with external cooling fins

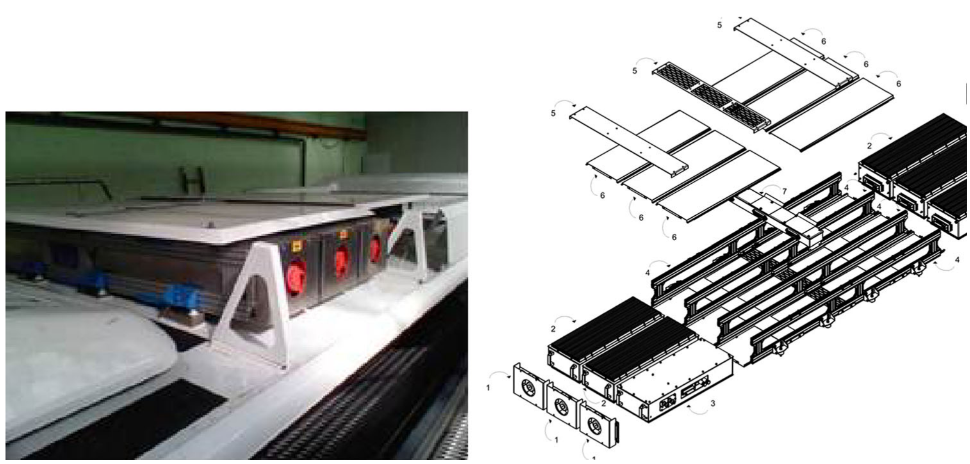


Fig. 6 An EDLC system on the roof of a bus and its exploded view

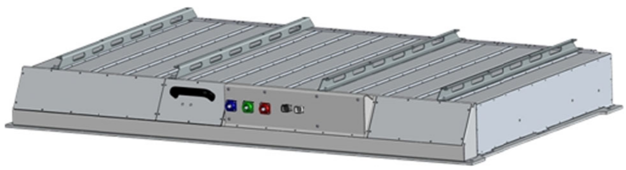


Fig. 7 The ‘standard’ modules under a hood, also known as the Bluways EDLC system

Table 1 Air cooling for different box designs

Box design	Large box	Standard	Compact
Heat exchange surface	2.6 m^2	0.4 m^2	0.25 m^2
Cooling power at natural convection		12 W/m^2 K 4.8 W/K	12 W/m^2 K 3 W/K
Cooling power at 3 m/s air speed	8.5 W/m^2 K 22 W/K	23 W/m^2 K 9.2 W/K	31 W/m^2 K 7.7 W/K
Losses at 150 A RMS	384 W	137 W	124 W
End temperature rise with natural convection		29 K	44.5 K
Test series length		180 min	165 min[a]
End temperature rise at 3 m/s air speed	17.5 K	15.3 K	16 K
Test series length		180 min	188 min

[a] Test interrupted due to over temperature

Fig. 8 The “standard” 20 EDLC cell module in a wind tunnel

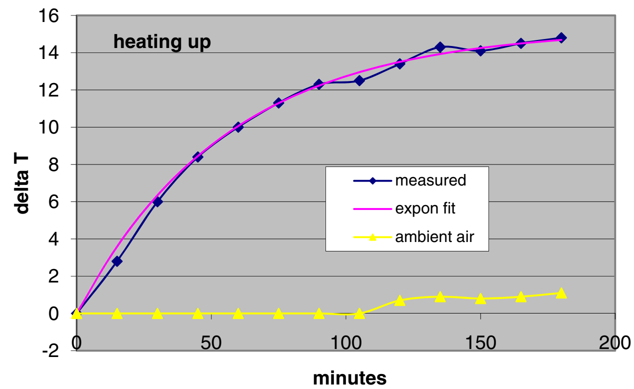


Fig. 9 Experimental determination of temperature rise of a “standard” 20 EDLC cell module at a continuous 150 A current and with 3 m/s external convection. Setup is shown in Fig. 8. Temperature rise end value and time constant are derived from the exponential fit

absorbed by dampers, but to guarantee the degree of protection under all driving conditions, EPDM sealing is used.

4.2 Cooling

The limiting factor as to the performance of an EDLC is mainly the thermal limits, especially when the EDLCs are cycled rapidly compared to their thermal time constant. In the applications described in Sect. 3, this is always the case.

The most basic concept for cooling EDLC systems is the open one (Fig. 4): air is drawn through the system. This may be fine for California and Nevada but is surely not suitable for use in Europe.

It is important to note that EDLCs conduct their heat to their terminals. Therefore, in the modular boxes, heat is removed from the terminals. In the first setup, capacitors are packed together by an aluminium bus bar connecting the terminals. The bus bar is in contact with the module housing through an electric isolator.

The spacing of the capacitors in the ‘standard’ 20 cell module was optimised towards the cooling surface, resulting in a larger footprint than is required as a minimum. The experimental compact module (or C-box) was built to explore the limits of the design (Fig. 5). This C-box has the smallest possible footprint and contains only 18 capacitors assuming that with an ideal balancing circuit, capacitors can safely be operated up to their maximum voltage.

Table 1 compares the cooling aspects of the three different mechanical designs: the first generation 56 cell C-box, the standard 20 cell C-box and the compact 18 cell C-box. The thermal data for the cooling fins are derived from the manufacturer’s data sheet the other data are empirical as measured in the Vito ENE battery testing lab in 2009. The box was placed in a wind tunnel with an air speed of 3 m/s, see Fig. 8. Figure 9 shows a thermal response test. The temperature end values summarised in Table 1 were determined using an exponential fit on a dataset with a length of at least three times the time constant of the process (95 % of the temperature rise) or until the cell’s maximum temperature was reached.

Since the maximum allowed capacitor temperature is limited to 65 °C, a temperature rise of 30 °C is acceptable. Ageing of EDLCs is significantly influenced by temperature [41–43]. As the cooling fins of the large C-box are mounted horizontally, cooling this design by natural convection is insufficient. Only the ‘standard’ design can be operated up to 35 °C ambient temperature at 150 A RMS

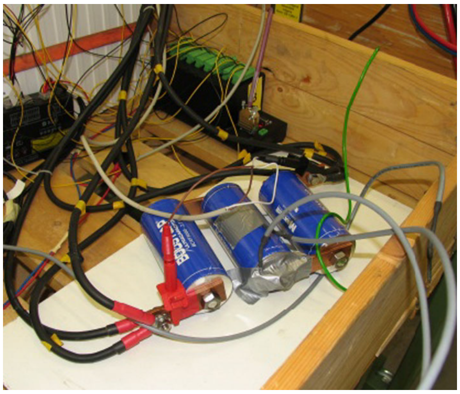


Fig. 10 Three EDLCs in series, the middle one equipped with a temperature sensor on the housing and on a terminal

Fig. 11 **a** The temperature response for a repetitive charge/discharge ▶ cycle. The highest temperature is measured by the sensor on the terminal, the other one is on the cylindrical housing of the EDLC. The temperature profiles are corroborated by Lajnef. **b** The temperature response for a repetitive charge/discharge cycle on a capacitor with an insulated housing. As long as the temperatures are low, so when only limited cooling of the terminals is possible, the temperature of the terminals rises faster than that of the housing, indicating a considerable heat production at the terminals

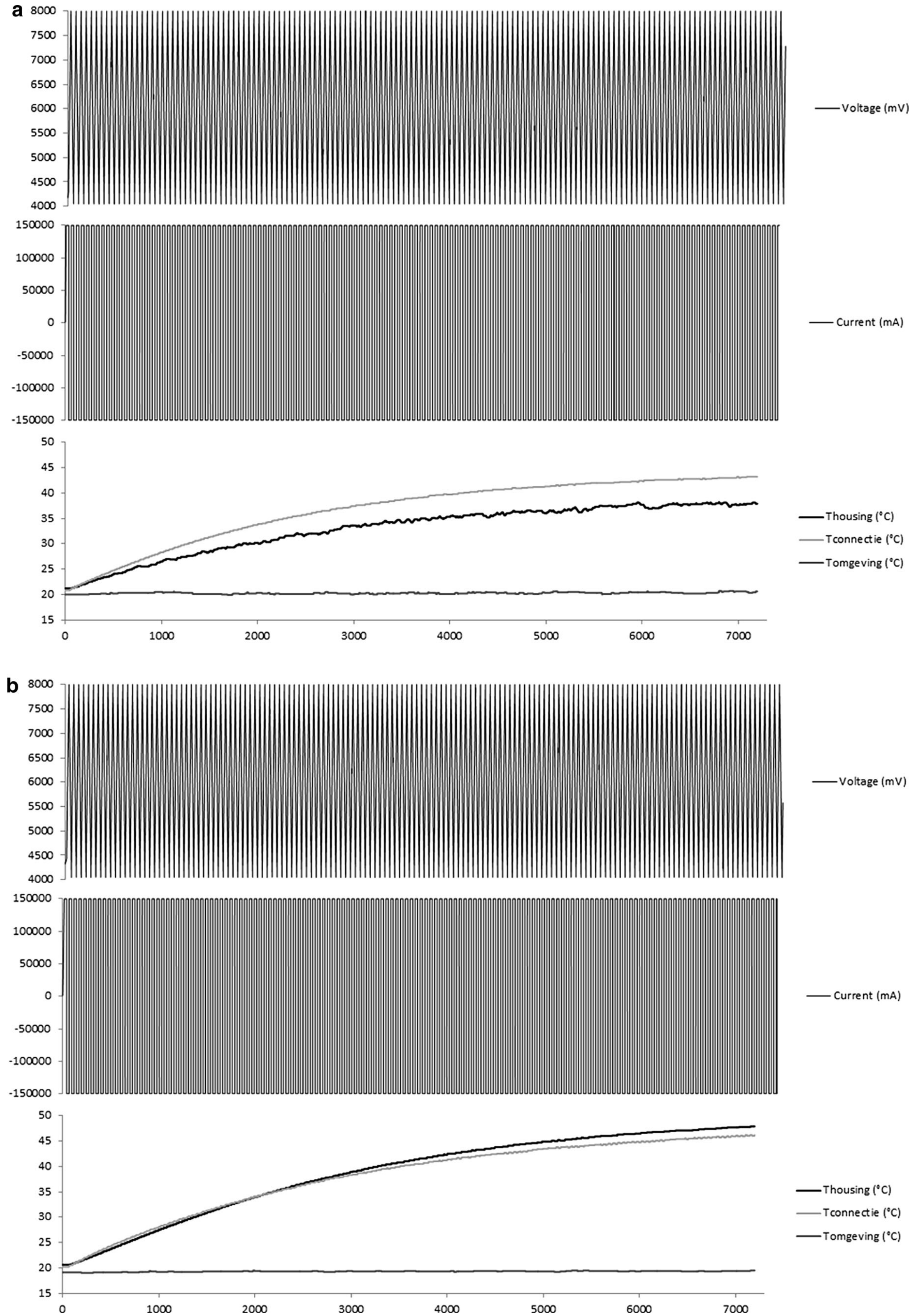
with natural convection cooling only. These results have been confirmed by follow up in the field.

The terminals of capacitors, carrying a high current, are generally hotter than the housing of the capacitor. This is easy to understand by considering the mechanical structure of the cylindrical EDLC cells. Heat is conducted more easily in an axial direction than in the radial direction so it is directed towards the terminals. The terminals themselves can be considered to be current collectors, so the current density and heat production in the terminals is high with only a limited heat exchange surface compared to the cylindrical part of the housing. Figure 10 shows a setup of three EDLCs connected in a series with a continuous 150 A current flowing through them. A thermometer is mounted on the housing and the positive terminal of the middle EDLC. Figure 11a clearly shows that the temperature on the terminal rises considerably higher than the temperature of the housing. This is consistent with Lajnef et al. [44]. An additional test has been performed using the same repetitive charge/discharge cycle on an insulated EDLC. Figure 11b shows the evolution of the temperature of an EDLC with insulated housing under the same load conditions as in Fig. 11a, i.e. at 150 A continuous current. In this case the terminal is cooled by natural convection, the housing is not cooled. Initially, the temperature of the terminal rises faster than that of the housing, clearly indicating that heat produced at the terminals contributes significantly to the temperature rise of the system. Finally, the housing becomes hotter since it can only loose its heat towards the terminals in the insulated case. Comparing the difference of end temperatures in Fig. 11a, b reveals that significantly more heat is conducted away from the terminals towards an uninsulated housing than is conducted towards and through the terminal in case of an insulated housing. It can therefore safely be deducted that keeping the terminals of an EDLC cool is an efficient way to keep the capacitor cool and thus to guarantee maximum life expectancy.

The capacitors of the 'standard' 20 cell EDLC module are actually 2 °C colder than the data of Table 1 suggest, as the temperatures have been measured on the terminals. Also, in truck and bus applications, there will always be some forced air flow due to driving. Although the internal resistance of EDLCs exhibit a negative temperature coefficient [45], variations in internal resistance of capacitors may produce higher temperatures locally. This is why the 'standard' boxes contain three temperature measurements each.

The fact that the EDLC system can be operated without fans reduces both investment and operating costs. The fans are basically the only parts of the EDLC system that need maintenance, as dirt, twigs, leaves, plastic bags, etc., may get into them. The fan's power consumption can be viewed as an increase in the EDLC's system losses of more than 30 %.

In some areas of Europe, even the 'standard' box with natural convection cooling may not provide sufficient cooling. So, the option of forced ventilation has been examined, which provides a suitable solution, but water cooling has also been examined. The potential advantage of water is the ability to cool to a lower than ambient temperature by connecting it to the bus or truck's air conditioning system. A calculation model was constructed and empirical data were collected for the compact box design. Both show that a temperature difference between capacitor terminals and the water would be 8 °C. The addition of water cooling should not restrict the exchangeability of the boxes on the system. Water would need to be routed close to the terminals but obviously not in electric contact with the terminals or bus bars. As a result, the coolant was routed outside the compact box set-up, hence this large temperature difference. If water cooling were to be used without connection to a heat pump, a relatively large radiator would be needed to cool the water, also introducing a serious temperature difference compared to the ambient air. Therefore, the benefit of water cooling of compact boxes compared to natural cooling of standard C-boxes is not considered to be an advantage.


a
b
Voltage (mV)
Current (mA)
Thousing (°C)
Tconnectie (°C)
Tomgeving (°C)
8000
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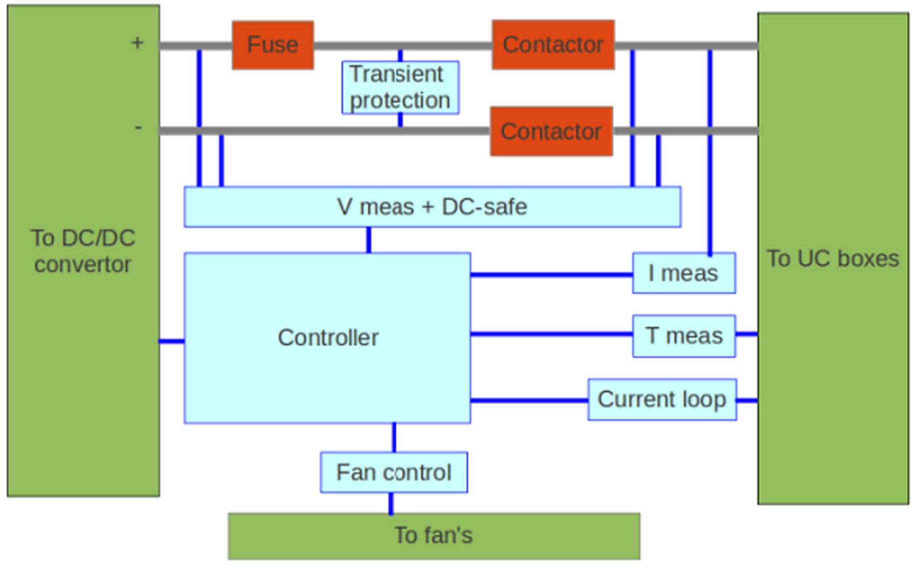

Fig. 12 The diagnostics block diagram for an EDLC system

The superior cooling properties of the ‘standard’ box are due to the very large contact area between the bus bars and the C-box’s housing and the fact that these parts are glued together with an appropriate electric isolator between them, which provides excellent thermal conductivity.

5 Discussion

5.1 Comparison of concepts

Mechanical concepts allowing easy replacement of capacitor modules are to be given preference. As many EDLC systems are mounted on vehicle roofs, EDLC modules should be portable. Air cooling of EDLC systems is the preferred method, as explored in the previous section. Designing the interconnections between capacitors to optimise cooling, thereby spacing capacitors in order to allow the creation of sufficient heat exchange surface, is the most effective way of cooling larger storage systems based on multiple EDLCs. EDLC modules containing enclosed capacitors, i.e. capacitors surrounded only by other capacitors, cannot be cooled sufficiently in order to sustain high power combined with short cycles. No forced air cooling is needed for the hybrid bus application. Such cooling quickly leads to a loss of 30 % in the energy gain obtained by the EDLC system. Water cooling should only be considered if cooling below ambient temperature is required, and then in combination with a heat pump.

5.2 Electric diagnostics

It is common practice to include self-diagnostics in this type of devices. As this EDLC is primarily designed for heavy duty automotive applications, it is interfaced to the vehicle using a CAN bus supporting J1939. The diagnostics carried out relate to:

- *Vehicle interface* CAN bus and ignition signal
- *Temperature* Up to 42 sensors are provided in case of the ‘standard’ box
- Electric isolation
- Current, voltage and their relationship
- Fan rotation if applicable

Multiple freeze frames can be stored to diagnose and back-track problems. This is in particular very useful for temperature-related issues. A block diagram of the diagnostics is shown in Fig. 12.

The EDLC system features a contactor that can be actuated by a CAN bus message. To prevent short circuit conditions, the voltage on both sides of the contactor should be approximately equal before closing it, thus requiring two voltage sensors. In the ‘standard’ box, one of them is an LEM LV-25; the other is part of the isolation monitoring. When the contactor is closed, these sensors are redundant so they can monitor one another. The voltage measurement is used to derive SOC and to protect against overvoltage by transmitting this value to the DC/DC converter. In view of the utmost importance of the voltage measurement, current integration should be used to check for rationality of the voltage sensors.

The isolation measurement is performed using DC-safe® [46] in the Bluways systems. Although DC-Safe introduces a small controlled isolation error in order to diagnose the real errors, it is fully compatible with the Unece Regulation R100 [47]. The advantage of DC-safe in this application is that it is capable, using only software, of determining the physical location of the isolation error within the string of

capacitors. As a result, it is not necessary to systematically disconnect boxes from the system in order to locate the box with the isolation fault which needs replacement. This presents a huge advantage in service and maintenance.

Finally, the derivative of voltage with time is monitored. High values of d*U*/d*t* indicate either a high internal resistance or a decreased capacitance of the system. Relating $U(t)$ to $I(t)$ makes it possible to determine which of these two errors occurred. In either of these cases, a high d*U*/d*t* indicates a major problem in the system requiring immediate response.

5.3 Thermal diagnostics

The system temperature is measured by three sensors in every one of the IP54 boxes. This allows rationality checks of the sensors when the system is started.

Abnormal temperature rise or temperature difference triggers CAN messages, instructing the Elfa DC/DC converter [37] to limit the current in or out of the EDLC.

Where applicable, fans are equipped with a pulse output indicating their rotation speed. This provides a simple means of determining mechanical blockage in a fan. Air flow deficiencies can only be diagnosed through abnormal temperature rise.

6 Conclusion

Mechanical concepts allowing easy replacement of capacitor modules are to be given preference. As many EDLC systems are mounted on vehicle roofs, EDLC modules should be portable, hence contain a limited number of capacitors.

EDLC systems need to be sealed (IP54) to comply with operational requirements, thus requiring special attention to cooling aspects. It has been shown that in many cases air cooling can be sufficient if certain design constraints are respected. This is based on four lay-outs that were studied in relation to the thermal response.

A good design enables an EDLC system to be operated without fans, even in the case of completely sealed boxes (IP54). This reduces both investment and operating costs. The fans are basically the only parts of the EDLC system that need maintenance. The fan's power consumption can be viewed as an increase in the EDLC's system losses of more than 30 %.

The aim of using EDLCs in these applications is to reduce energy consumption. This is done primarily by relying on braking energy recovery; operation of the combustion engine at its sweet spot contributes only marginally to energy savings.

An amount of 0.5 kWh of energy is sufficient to accelerate an articulated bus on a flat road to a speed compatible with inner city operation. For any other circumstances, an energy storage system considerably larger than 0.5 kWh would be required.

Diagnostics can easily be introduced with the help of the existing sensors if a good understanding of the system has been gained. This enables safe and reliable EDLC operation.

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